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Method for determining the refractive index during interferometric length measurements, and interferometer arrangement therefor

The invention relates to a method for determining the refractive index and/or compensation of the influence of refractive index during interferometric length measurements with the aid of an interferometer to which there are applied at least two measuring beams having at least defined frequencies approximately at a harmonic ratio to one another, and at whose output phases for the at least two measuring beams are evaluated, the interferometric phases being multiplied in an interferometrically fashion corresponding to the harmonic ratio of the frequencies of the measuring beams and at least one phase difference of the phase values thus formed being examined.

The invention also relates to an interferometer arrangement for carrying out the method having at least one coherent radiation source for generating at least two measuring beams having defined frequencies approximately at a harmonic ratio to one another and having an interferometer whose output signals are passed to a beam splitter separating the measuring beams, the separated measuring beams being passed to optoelectronic transducers, and at least one of the output signals of the optoelectric transducers being fed to a multiplier corresponding to the harmonic ratio of the frequencies of the measuring beams.

It is known to use an interferometer to carry out distance measurements and/or measurements of changes in physical lengths. In the case of such a measurement, the optical path length is measured that is composed of the physical path length and the integral refractive index of the medium on the measured path length. The influence of the refractive index on the measurement

can be eliminated by virtue of the fact that the interferometric measurement is carried out with two defined different wavelengths. Since the refractive index depends on the wavelength, while the physical path length is independent of the wavelength, it is thereby possible for items of information relating to the physical path length and refractive index to be separated from one another.

US 4,948,254 describes an apparatus that operates using this dispersion method. The two wavelengths are supplied by an argon ion laser in combination with a frequency doubler crystal. Two waves that are basically phase-locked are produced for the interferometry by using a fundamental wave and a frequency-doubled wave. The doubler crystal is located at the start of the measuring distance at the measuring arm of a two-beam interferometer. The outgoing fundamental wave produces a colinearly running harmonic in the crystal. Both waves traverse the measuring distance. Upon returning through the crystal, the fundamental wave produces a second harmonic, which has a phase difference with respect to the first harmonic because of the dispersion in the medium being traversed. This phase difference, which is to be measured, constitutes the measuring signal. It is a measure of the dispersion and thus of the refractive indices. The phase difference is dependent only slightly on other influences such as the position and state of movement of the interferometer, and so the phase difference constitutes a useful measuring signal for an accurate measurement. However, there is the problem that determining the phases accurately is complicated and saddled with fundamental measurement uncertainties.

US 5,404,222 describes a similar system, in which the double crystal is traversed before the light used

enters the interferometer. Moreover, frequency doubling takes place at the output of the interferometer.

A so-called superheterodyne interferometer is known from US 5,838,485, for example, for the purpose of improving the measuring accuracy. Here, as well, a two-wavelength interferometer with harmonically corrected optical waves is used in order to compensate the influence of the refractive index by means of the dispersion method. With the superheterodyne interferometer, the interferometric phases of the optical fundamental wave and harmonic are respectively mapped onto high-frequency heterodyne frequencies. The interferometric phase of the heterodyne signal of the fundamental wave is doubled. The difference between this doubled phase and the phase of the heterodyne signal of the harmonic is proportional to the dispersion. The advantage of the superheterodyne interferometer consists in that the sensitivity of the compensation of the refractive index with reference to the mechanical stability of the interferometer is much lower. However, the accuracy of measurement that can be achieved is limited by the determination of the phase difference. For the high frequency signals, the phase measurements must be performed more accurately by 1 to 2 orders of magnitude, than for the actual length measurement. The measurement of two independent phases is required in order to determine the phase difference. Possible nonlinearities in the phase measurement influence the measurement uncertainty. The differential phase changes periodically with the measuring distance and so the determination of the refractive index is not unique. Furthermore, the measuring distance must be changed in order to determine the refractive index. The method is therefore suitable only for displacement measurements accompanied by refractive index compensation, but not for position measurements

accompanied by refractive index compensation, for example in an interferometer with absolute measurement.

Furthermore, US 2002/0001086 A1 discloses combining a two-wavelength interferometer with a refractometer that is placed in the vicinity of the distance to be measured interferometrically. The refractometer, which comprises a balanced interferometer of fixed path lengths, the reference distance running in vacuum and the measuring distance running in the ambient air, serves the purpose of measuring the long term changes in the refractive index, and can be used to determine the inverse dispersion A when the composition of the air is changing. The refractive index can be determined uniquely and in absolute terms given this supplement.

It is the object of the present invention to improve a method and apparatus of the type mentioned at the beginning such that the influences of refractive index can be more accurately compensated for precision length measurements.

According to the invention, in order to achieve this object the method of the type mentioned at the beginning is characterized in that at least one of the measuring beams is of variable frequency, and in that from the phase difference formed a control signal is formed in order to vary the frequency of the variable frequency measuring beam and is used to control the frequency such that the phase difference vanishes.

Furthermore, according to the invention in order to achieve the object an apparatus of the type mentioned at the beginning is characterized in that the frequency of at least one of the measuring beams can be varied by means of a frequency controller, and in that a phase comparator for the phases of the output signals of the optoelectric transducers, is used to generate a control

signal representing a phase difference, which control signal is fed to the frequency controller to form a control loop for the interferometric phases.

According to the invention, an interferometric phase-locked loop is implemented which ensures that the integral optical wavelengths of the two beams circulating in the interferometer are exactly harmonically correlated along the measuring distance. The correlation corresponds to the harmonic frequency ratio of the fields of the two-frequency radiation source. For this purpose, the frequency of one of the measuring beams is adjusted by a certain frequency amount, the offset frequency. The differential frequency between the exactly harmonic frequency ratio and the frequency set by the control loop is a direct measure of the integral refractive index on the measuring distance. The offset frequency can be measured easily, and is, in particular, independent of the length of the measuring distance and of mechanical instabilities of the interferometer. Since, according to the invention, the measurement of the refractive index can be reduced to a frequency measurement, a higher measuring accuracy is achieved in principle, given that frequencies are physical quantities that can be measured very accurately. Furthermore, by contrast with the measurement of a periodic phase, the frequency measurement is a priori unique and measurement can be carried out in principle without effect modulation.

The measurement of the offset frequency is preferably performed by virtue of the fact that at least one reference beam is generated at a frequency that corresponds approximately to the frequency of one of the measuring beams and is coupled to the frequency of another measuring beam, and in that a frequency difference is measured between the frequency of the

reference beam and the frequency of the corresponding measuring beam.

The method according to the invention and the interferometer arrangement according to the invention can be modified by applying the superheterodyne principle. In particular, it is possible in this case for high frequencies that are at the same harmonic ratio to one another as the frequencies of the measuring beams to be modulated onto the superimposed measuring beams in a reference branch of the interferometer.

It is also possible in a further modification of the present invention to make use of different polarization components, one polarization component being displaced from the other by $\pi/2$ by means of a λ retardation plate. It is thereby achieved that there are always available for accurate evaluation signal components that are not zero and can therefore be effectively measured.

The invention is to be explained in more detail below with the aid of exemplary embodiments illustrated in the drawing, in which:

figure 1 shows a schematic of an interferometer arrangement according to the invention,

figure 2 shows a schematic of an embodiment of the interferometer arrangement according to the invention, as a superheterodyne interferometer with two laser sources,

figure 3 shows a variant of the embodiment in accordance with figure 2, with a single laser source.

Provided in the embodiment in accordance with figure 1 as coherent radiation source is a laser L1 that emits a laser beam at frequency v_1 as reference beam, and at a second frequency v_2 as first measuring beam. The laser L1 can be, for example, a second harmonic generator (SHG) laser that also emits a frequency-doubled field $v_2 = 2v_1$ in addition to its fundamental frequency v_1. However, the application of the invention is not limited to frequency doubling. What is essential is a harmonic correlation of the frequencies in the general form of $k1 \cdot v_1 = k2 \cdot v_2$, k1, k2 being natural numbers. In a preferred form that is easy to implement, it holds that $v_2 = N \cdot v_1$ (N being a natural number > 1).

A second laser source L2 emits a laser beam at a third frequency v_3 that corresponds to the frequency v_1.

In the exemplary embodiment illustrated, the output frequency of the laser L2 can be controlled by a frequency controller 11. The frequency controller can be an acousto-optic modulator (AOM), but also a frequency control input of a laser L2 of tunable frequency.

The output beam of the laser L1 passes to a dichroic beam splitter DST 11 that deflects the beam of the laser L1 at frequency v_1 as reference beam, and passes the beam at frequency v_2 as first measuring beam. The first measuring beam v_2 traverses a second dichroic beam splitter DST12 and passes into an interferometer 13.

The frequency $v_{3'}$ of the second laser L2 is influenced by the frequency controller 11 and, as frequency v_3, emerges as second measuring beam from the frequency controller 11. It is split by a neutral beam splitter ST11 into two components of which one is deflected out of the beam path and guided onto a mirror ST11, the

partial beam passing to a further neutral beam splitter ST12, as a result of which the deflected component of the second measuring beam v_3 is superimposed collinearly on the reference beam deflected by the dichroic beam splitter DST11. The superimposed measuring beam passes to a photodetector PD11. If the frequencies v_3 and v_1 correspond, a differential frequency $\Delta v = \phi$ is produced. However, if a frequency deviation is present, an oscillation frequency $\Delta v = |v_1 - v_3|$ is measured with the aid of a frequency counter FZ.

The portion of radiation for the second measuring beam v_3 that is transmitted through the beam splitter ST11 is collinearly superimposed on the first measuring beam v_2 via a mirror S12 and the dichroic beam splitter DST12, and so both measuring beams v_2, v_3 pass to a beam splitter ST13 of the interferometer 13. The neutral beam splitter ST13 splits the incoming measuring beam (formed from the superimposed measuring beams v_1, v_2) into a reference arm guided to the reference mirror S13 and into a measuring arm of the interferometer 13, which is formed by a measuring mirror S14. The beams reflected by the reference mirror ST13 and by the measuring mirror S14 are superimposed by the beam splitter DST13 and pass to a dichroic beam splitter DST13 at the output of the interferometer 13. The dichroic beam splitter DST13 separates the two frequencies v_1, v_3 from one another, since the frequency v_3 is deflected by the dichroic beam splitter DST13 onto the photodetector PD13 while the frequency v_2 of the first measuring beam traverses the dichroic beam splitter DST13 and passes to a photodetector PD12.

The phases $\phi 2$ and $\phi 3$ produced by the measuring beams v_2, v_3 are separated by means of one of the known methods for detecting the interferometric phase, this being

done with the aid of suitable evaluation electronics 14, 15, and processed.

For the phases, it holds that

$$\phi 2 = \frac{4\pi \cdot L \cdot n_2 \cdot \nu_2}{c} \text{ and}$$

$$\phi 3 = \frac{4\pi \cdot L \cdot n_3 \cdot \nu_3}{c},$$

n_2, n_3 being the integral refractive index along the distance L for the optical frequency ν_2 and ν_3, respectively, and c being the speed of light (in vacuum).

Since the frequencies ν_2 and ν_3' are harmonically correlated to $\nu_2 = N \cdot \nu_3'$, and the frequency control range of the frequency controller 11 effects only small changes in frequency, as will be explained in yet more detail, it holds that $\nu_2 \approx N \cdot \nu_3'$.

It can also hold that

$$\phi_2 \approx N \cdot \phi_3.$$

The interferometric phase ϕ_3 is not multiplied in a multiplying stage 16 by the factor N, and the phase thus formed is compared with the phase ϕ_2 in a phase comparator 17 by forming the difference

$$\Delta\phi = \phi_2 - N \cdot \phi_3$$

This differential signal is amplified via a control amplifier 18 that is a PI amplifier (Proportional Integral Amplifier) in the exemplary embodiment illustrated, and is fed to the frequency control stage 11 such that

$$\Delta\phi = \phi$$

holds as control criterion. The result is the implementation of an interferometric phase-locked loop that ensures that the integral optical wavelengths of the two beams circulating in the interferometer are exactly harmonically correlated along the measuring distance L of the interferometer 13 in accordance with

$$N \cdot \lambda_2 = \lambda_3, \lambda_2 = \frac{c}{\nu_2 \cdot n_2}, \lambda_3 = \frac{c}{\nu_3 \cdot n_3}.$$

It is thereby possible to calculate the integral refractive index n2 from

$$n_2 = \frac{\nu_2 + N \cdot \Delta\nu}{\nu_2 + N \cdot \Delta\nu - N \cdot A \cdot \Delta\nu}$$

from the knowledge of the optical frequency ν_2 and the measurement of the frequency difference $\Delta\nu$ in the frequency counter FZ. The inverse dispersion A that is included in this expression and defined as

$$A = \frac{n_2 - 1}{n_2 - n_3}$$

can be calculated for measuring distances in air of normal composition from the so-called modified Edlen formula (compare G. Bönsch, E. Potulski "Measurement of the refractive index of air and comparison with modified Edlen's formulae", Metrologia 35 (1998), 133-139), or can be measured with the aid of a suitable apparatus (compare US 2002/0001086 A1).

The physical path length difference L in the interferometer is therefore yielded as

$$L=\frac{\phi_2\cdot c}{4\pi\cdot n_2\cdot \nu_2}=\frac{\phi_2\cdot c}{4\pi\cdot\dfrac{\nu_2+N\cdot\Delta\nu}{\nu_2+N\cdot\Delta\nu-N\cdot A\cdot\Delta\nu}\cdot\nu_2}=\frac{c\cdot\phi_2\cdot(\nu_2+N\cdot\Delta\nu-N\cdot A\cdot\Delta\nu)}{4\cdot\pi\cdot\nu_2\cdot(\nu_2+N\cdot\Delta\nu)}$$

Given a displacement measurement of the measuring mirror S14 or a position measurement, it is therefore possible with the aid of the invention for both the refractive index and the refractive index fluctuations to be compensated with high precision along the distance to be measured. In the case of the exemplary embodiment illustrated in figure 2, the first laser L1 emits the frequencies v_1, v_2, while the second laser L2 is designed as a laser of tunable frequency and therefore emits the frequency v_3. As in figure 1 - the dichroic beam splitter DST21, the neutral beam splitters ST21 and ST22 and the mirror S21 are provided for measuring the frequency difference $\Delta v = |v_3-v_1|$. The optical frequency difference is converted electrically by the photodetector 21 and evaluated electrically in the frequency counter FZ. The second measuring beam v_3 is not superimposed until in the measuring beam v_2 via the mirror S22 and the beam splitter ST23, and is guided in this form to the interferometer 13'. However, the superimposed beams are also guided via a mirror S23 onto an acoustooptic modulator (AOM) 20 that shifts the frequency of at least portions of the two beams. As a result, the frequency of the beam at optical frequency v_2 is shifted by the (radio) frequency 2Ω, and the frequency of the beam at optical frequency v_3 is shifted by the frequency Ω. For this purpose, the frequencies Ω, 2Ω are led via a high frequency generator 21 to a control input of the AOM 20. The two optical beams traverse the AOM collinearly. Since, in accordance with the exemplary embodiment illustrated, the optical frequencies v_3 and v_2 form to a very good approximation the same frequency ratio as the high frequencies Ω and 2Ω, the Bragg condition in AOM is, as further explained below, simultaneously filtered

electronically and optically in one spatial direction for the optical frequency v_3 and the high frequency Ω, and therefore does not disturb the measurement method described here.

The two partial beams collinearly superimposed in the beam splitter ST23 and guided directly into the interferometer 13′ pass through the beam splitter ST24 and are reflected at a reflector 21, which can be displaced within the measuring path length L, and guided through the beam splitter ST24 onto a dichroic beam splitter 22. The reflector 21 is designed as a silvered roof prism in the exemplary embodiment illustrated. The reflected measuring beams are collinearly superimposed at the output of the beam splitter 24 with the reference beams modulated by the AOM 20. The dichroic beam splitter DST 22 separates the beams into two partial beams that are converted into electric signals by means of photodetectors PD23 and PD24. The component passing through the dichroic beam splitter DST22 has a beat at the frequency 2Ω. This is extracted from the electric signal at the frequency 2Ω by means of a suitable bandpass filter BP21. Similarly, the beams reflected at the dichroic beam splitter DST22 generate at the detector PD23 a beat signal of frequency Ω that is once again extracted from the detector signal by means of a suitable bandpass filter BP22 of frequency Ω.

With this heterodyne interferometer, the interferometric phase shift, produced by a displacement of the reflector 21, between reference beam and measuring beam is mapped onto an equally large phase shift of the heterodyne frequency. Since it holds that v_2 is approximately $2 \cdot v_3$, and that it also holds for the optical wavelengths that $\lambda_3 \approx 2 \cdot \lambda_2$, given a displacement of the reflector 21 the resulting phase shift of the heterodyne signal of frequency 2Ω is

approximately twice as large in the double heterodyne interferometer described here than the resulting phase shift in the heterodyne signal of frequency Ω. The latter phase shift is doubled with the aid of a high frequency frequency doubler 22, and the phase of the doubled signal is compared with the phase of the heterodyne signal of frequency 2Ω with the aid of a phase comparator DBM in the form of a doubly balanced mixer. The phase comparator includes a downstream low pass filter with a suitable cutoff frequency $<< 4\Omega$.

With the aid of a PI controller 23, the frequency of the beam v_3 emitted by the laser L2 is varied until the output signal of the phase comparator DBM vanishes and so it holds for the optical wavelengths that $\lambda_3 = 2 \cdot \lambda_2$. A small path length difference ΔL of the measuring length L of the interferometer 13' can be set for the purpose of producing the uniqueness of the control, which is not inherently ensured by the periodic output signal of DBM. The path length difference ΔL must thus be prescribed the condition for the ambiguous output signal DBM a larger frequency difference Δv to be set as maximum differential frequency Δv_{max}. Control is uniquely possible in this case with only one Δv.

An interferometric phase-locked loop which ensures that $\lambda_3 = 2 \cdot \lambda_2$ holds is thus implemented again. It holds that:

$$n_2 = \frac{\nu_2 + 2 \cdot \Delta\nu}{\nu_2 + 2 \cdot \Delta\nu - 2 \cdot A \cdot \Delta\nu}$$

and that

$$L = \frac{c \cdot \phi_2 \cdot (\nu_2 + 2 \cdot \Delta\nu - 2 \cdot A \cdot \Delta\nu}{2 \cdot \pi \cdot \nu_2 \cdot (\nu_2 + 2 \cdot \Delta\nu)}$$

for the physical path length difference L in the interferometer. The phase ϕ_2 required therefor can be obtained by means of known techniques, for example by means of a commercially available I/Q demodulator 24.

A possible modification of the design of the invention in accordance with figure 2 that manages with only one laser L1 is illustrated in figure 3. The beam of frequency v_1 emitted by the laser L1 is frequency shifted by the frequency Δv by means of a very wide band, for example acoustooptic frequency shifter AOM 36, such that $v_3 = v_1 + \Delta v$.

Such wide band frequency shifters with a voltage controlled microwave driver (VCO) 35 are commercially available. Otherwise, the exemplary embodiment corresponds substantially to figure 2, the measure of the frequency difference that serves as measuring signal resulting directly from the frequency for the VCO 35.